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Simulating the performance of a p_T tracking trigger for CMS

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ABSTRACT: The Super-LHC (SLHC) is a proposed Large Hadron Collider (LHC) accelerator upgrade to increase the machine luminosity by an order of magnitude to $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The CMS experiment at the LHC is also planning an upgrade of its tracking system in expectation of this development. The increased particle fluxes and radiation environment will necessitate the complete replacement of the current CMS tracker while presenting the design of a new tracker with severe challenges. Power consumption is one of the main challenges for the tracker readout system since a higher granularity detector will be required. Physics performance must not be compromised so the tracker material contribution should be lowered where possible. In addition, it is likely that the Level 1 system will require information from the tracker in order to reduce the trigger rate. A method of reducing the on-detector data rate for input into a L1 trigger using closely separated pixel layers is presented. A detailed simulation of a concept tracker geometry has been developed and the triggering performance has been estimated. The simulations report that the presented tracking trigger layer would be viable for use at SLHC. A layer would be capable of reducing the detector data rate by a factor of ∼20 while maintaining a track finding efficiency in excess of 96% for tracks with $p_T>2$ GeV/c. The information provided by a single stacked layer would not be useful for reducing the L1 trigger rate, but two stacked layers could be used to reconstruct tracks with $\delta p_T/p_T < 20\%$ for $p_T<20$ GeV/c and with sufficient resolution so as to match tracks with L1 calorimeter objects.

KEYWORDS: Trigger concepts and systems (hardware and software); Simulation methods and programs; Data reduction methods

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Contents

1 The Super-LHC

The proposed luminosity upgrade [1] for the Large Hadron Collider (LHC) is expected to take place in two phases over a 10 year period after LHC start-up. With an increase of a factor of 10 in luminosity, the LHC experiments will also require various upgrades in order to cope with the increased particle fluxes, data rates and years of radiation damage. The CMS experiment [2] is expected to replace its entire tracking system after an integrated luminosity of $\sim$500 fb^{-1} and its inner pixel detector at least once before this. Aside from the radiation tolerance of sensors and electronics, the most important challenges are the development of low power electronics and power distribution schemes to the front end. To remove increased heat loads within the system, cooling must be improved while tracker material must be reduced in order not to compromise physics performance.

The Level 1 (L1) system [3] is a customised hardware trigger designed to promptly ($< 4\mu$s) reduce the event rate before event reconstruction and processing on large CPU farms. It has been shown that the L1 trigger suffers from the increased pileup of up to 500 minimum bias interactions per bunch crossing at SLHC [4]. Raising transverse energy (E_T) and momentum thresholds (p_T) offer little reduction in rate while adversely affecting sensitivity to low mass discoveries and measurements at the LHC. Since tracking information is not currently used in the L1 trigger decision, it is hoped that its inclusion will stop the trigger exceeding its maximum 100 kHz rate. Providing tracking information to the trigger presents entirely new challenges in the design of an upgraded tracker. Specifically, the on-detector data rate must be reduced significantly for viable readout at the bunch crossing rate of 40 MHz. In addition, the tracking trigger must not contribute significantly to the power dissipation and material within the tracker and more importantly must not reduce tracking performance and resolution.

2 Stacked tracking trigger layers

Collisions at the LHC are predicted to produce a large number of low momentum particles that make up a significant fraction of hit data generated by the tracker (figure 1). Charged particles with

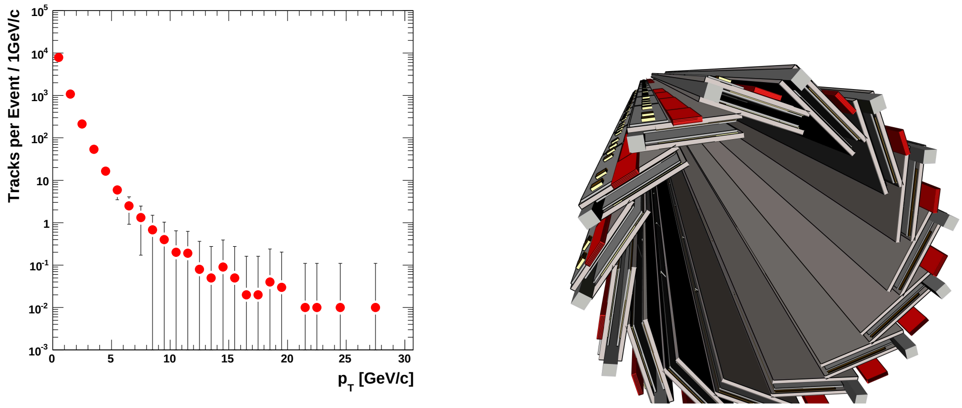

Figure 1. Left: The p_T spectrum (averaged per event) for all minimum bias particles that leave hits in a sensitive layer placed at a radius of 25 cm and at an average pileup of 400 p-p interactions per event. Events were simulated within a magnetic field of 4 T and a coverage of $|\eta| < 2.5$. Right: Visualisation of a GEANT defined stacked pixel layer including cabling, cooling and mechanical support.

transverse momentum p_T<0.7 GeV/c are considered uninteresting for the purposes of triggering since they fail to reach the outer sub-detectors due to the bending power of the 4 T magnetic field.

By correlating hits between closely spaced ("stacked") pixelated sensors, this low p_T background can be rejected by only selecting hits that lie within a few pixels of each other in the bending plane (r-ϕ). In a 4 T magnetic field, studies show that for a layer of stacked pixel sensors placed at 25 cm and a radial separation between sensors of $\sim$ 1 mm, a pixel pitch of order 100 μm in r-ϕ can be used to select tracks with transverse momentum greater than a few GeV/c [5, 6]. In this way, the on-detector data rate can be reduced by at least an order of magnitude before tracking information is forwarded to the L1 trigger for matching to other trigger objects.

In order to estimate the triggering performance of such layers, realistic simulations have been performed using a modified geometry within the CMS software environment (CMSSW). The concept tracker geometry includes two such stacked pixel layers at 25 cm and 35 cm, with full coverage up to $|\eta| < 2.5$, 100 μm thick sensors and pixels with 100 μm$\times$2.45 mm pitch in rϕ-z. Long pixels are used in order to minimise power requirements. With this granularity, the occupancy in a typical SLHC event at 25 cm is expected to be <1%. The inner tracker is comprised of four pixel layers and three pairs of pixel endcaps as defined in [7], with appropriate material description. The outer tracker is based on the current CMS outer silicon microstrip tracker barrel and endcaps. In the absence of a detailed layout of a stacked pixel module, the stacked layer material description is based on that of two standard pixel layers with shared mechanics and cooling.

As is standard in CMSSW, the simulation uses PYTHIA [8] for the generation of the Monte Carlo event while particle interactions with matter are simulated using the GEANT4 [9] package. A parametrised version of the GEANT software ("Fast Simulation") [10] can be also used although it should be noted that it does not consider out-of-time pileup and hence underestimates the occupancy by a factor of $\sim$2.5. In the following section, the definition of SLHC pileup conditions is taken to be an average of 400 minimum bias interactions per bunch crossing under the Fast simulation. The simulation includes Poissonian fluctuations in the number of interactions per event under

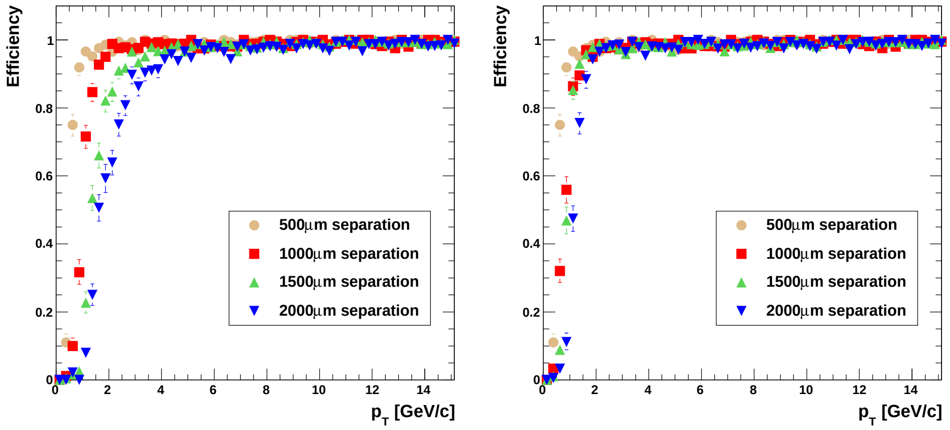

Figure 2. p_T discrimination performances of a stacked layer for; Left: single $\mu^{\pm}$ tracks at various sensor separations and a fixed 3 pixel row correlation window; Right: single $\mu^{\pm}$ tracks at various sensor separations where the correlation window is widened with sensor separation (see table 1). All results are for a stacked layer at 25 cm.

these conditions. All collision vertices are smeared along the z direction to approximate a Gaussian distribution centred at the origin with σ_z=53 mm.

The correlation algorithm to match hits between individual sensors and identify high transverse momentum candidates ("stubs") is described in further detail in [6]. Of particular importance is the r-ϕ or row correlation window which is the discriminator for measuring the track curvature in the magnetic field.

3 Simulated performance of a single layer

For a fixed row correlation window, increasing the sensor separation has the effect of increasing the p_T cut at which stubs are generated. Figure 2 (left) demonstrates how a stacked layer at 25 cm is expected to perform at discriminating against the transverse momentum of tracks for various sensor separations and a fixed row correlation cut. The result of the simulation using single muons validates those from previous studies [5].

The efficiency ε described in figure 2 is defined as the ratio of total number of tracks with Monte Carlo transverse momentum (p_T) which generate at least one pixel hit in the stacked pixel layer to the number of tracks with Monte Carlo transverse momentum (p_T) which generate at least one stub in the stacked pixel layer.

The row correlation window cut is another method of controlling the transverse momentum at which tracks are discriminated against. The difference is that while varying the sensor separation modifies the p_T cut continuously, changing the correlation window will modify the p_T cut in discrete steps, as defined by the pixel pitch. Figure 2 (right) and table 1 demonstrate that increasing the row window with sensor separation maintains p_T discrimination performance. Building a layer with a larger sensor separation but with a correlation window that can be varied may be more practical in terms of robustness to triggering demands and the physics at SLHC.

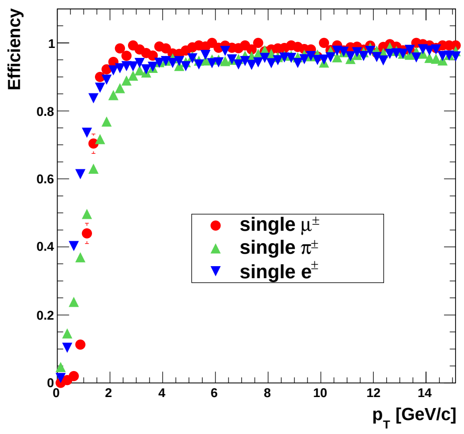

Figure 3. p_T discrimination performances of a stacked layer for single $\mu^{\pm}$, $\pi^{\pm}$ and $e^{\pm}$ tracks using a layer with a 2 mm sensor separation and a 5 pixel correlation window. All results are for a stacked layer at 25 cm.

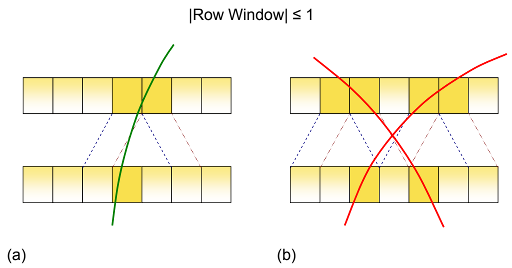

Figure 4. Illustration on the origin of duplicate and fake stubs; (a) demonstrates that if the row correlation window is $\geq \pm 1$, clusters of hit pixels can give rise to multiple stubs. The number of duplicates could be reduced to zero using a clustering algorithm either before or after correlation. Tracks which would not normally pass the correlation cut may still produce a stub if hits are incorrectly matched with those from another track (b).

Table 1 shows that for a fixed correlation window, a larger separation will increase the effective p_T cut and therefore reduce the number of generated stubs. However, if tracking isolation is required at L1, efficient triggering on tracks with transverse momenta of at least 2 GeV/c [11] will be necessary.The efficiency for triggering of tracks with p_T>2 GeV/c is also provided in table 1 along with the average ratio of duplicate and fake stubs (figure 4) to total stubs. The reduction factor is defined as the ratio of average number of hit pixels to the average number of generated stubs in a layer, per event. It is an indication of the reduction in the number of hits to be read out if correlation was to be performed on detector. An order of magnitude data rate reduction will be required if the readout system is to satisfy existing power and cabling constraints [6].

Figure 3 compares the performance for the stacked layer when selecting muon, pion and electron tracks by p_T. Although the difference appears minimal, the layer is less effective at rejecting low transverse momentum electrons and especially pions, compared to muons. Since the stacked trigger layer assumes an interaction vertex at the beam axis, the p_T of particles from secondary interactions or bremsstrahlung electrons can be reconstructed incorrectly. It is therefore important that the material in the inner detector is minimised.

Table 1. Trigger performance of a stacked layer at 25 cm. $\varepsilon_{\text{Muon}}$ is the efficiency for triggering on $\mu^{\pm}$ tracks with $p_T > 2$ GeV/c. The percentage of fake and duplicate stubs and the rate reduction factors are calculated from simulating the stacked layer in minimum bias events under SLHC pileup conditions. A configuration with 2 mm separation provides adequate performance, while allowing the option of varying the correlation window cut based on operating conditions and physics requirements.

Sensor Separation (μm)	Row Window (pixels)	$\varepsilon_{\text{Muon}}$ $p_T > 2$ GeV/c (%)	N_{Stubs}	Fake (%)	Duplicate (%)	Rate Reduction
1000	3	99.2	2670.5	6.6	30.9	22.0
1000	4	99.2	4150.9	5.6	36.6	14.2
2000	3	97.1	1054.1	23.3	22.4	54.4
2000	5	98.7	2248.3	18.1	28.0	25.5

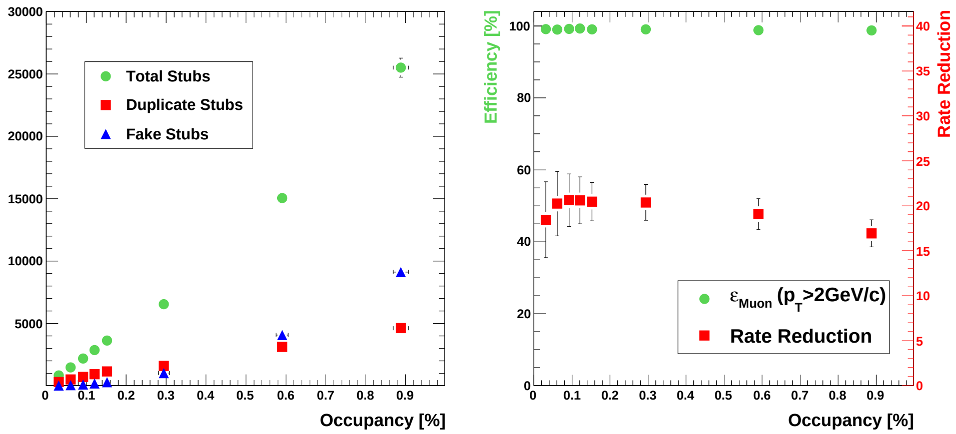

Figure 5. Left: Average number of generated stubs per event and; Right: Trigger efficiency for muons with $p_T > 2$ GeV/c (left scale) and rate reduction factor (right scale) as a function of average layer occupancy. Results are for a stacked layer at 25 cm with a sensor separation of 1 mm and a row correlation window of 3 pixels.

The trigger algorithm needs to be able to operate efficiently at any luminosity while still offering the same reduction in data output and must also be robust against any local or global fluctuations in occupancy. In the most extreme cases, it may be possible that the stacked layer will be subject to peak hit pixel occupancies of up to 0.63%±0.23%[6]. Figure 5 demonstrate that for occupancies up to 0.6%, the performance of the stacked tracker is robust against pileup. At occupancies approaching 1%, it is observed that the rate reduction factor is reduced slightly. This is due to a non linear increase in the number of stubs generated by fake correlations.

The disadvantage of using a single layer is that stubs contain no p_T information other than that they passed the cut. If they are to be used to reduce the L1 trigger rate, the occupancy per trigger region should be low. The calorimeter trigger tower offers the smallest trigger granularity in the CMS detector of which there are around 4000 compared to approximately 15,000 stubs at high occupancies. Figure 6 indicates to the origin of the large stub background. Over 85% of generated

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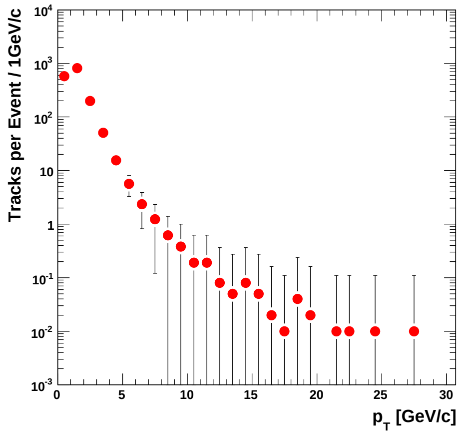

Figure 6. The p_T spectrum (averaged per event) for all minimum bias particles that generate stubs in a stacked layer under SLHC pileup conditions. Results are for a stacked layer at 25 cm with a sensor separation of 1 mm and a row correlation window of 3 pixels.

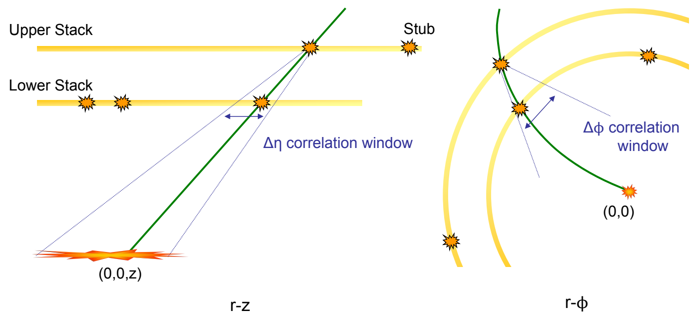

Figure 7. The double stack reconstruction method. Stubs from the inner stacked pixel layer which fall within a $\Delta\eta\Delta\phi$ window of a seed stub in the outer layer are correlated.

stubs are from tracks with transverse momentum below 2 GeV/c which pass the correlation because they are from secondary interactions. This motivates the investigation into the use of two stacked tracking layers to provide a better estimate of the track transverse momentum and reduce the data rate to the L1 trigger further. A fuller discussion of the impact of sensor and layer geometry choices, including sensor tilting, on performance is discussed further in [6].

4 Simulated performance of a double layer

In a double stack configuration, each layer would be able to provide the necessary data rate reduction required for transmitting tracking information off detector before correlation for track reconstruction. The advantage of this design would be that track p_T can be measured but no on-detector communication between layers would be needed, removing the need for high bandwidth links and a complex interconnection scheme between modules which greatly increase the power consumption and material of the system.

Table 2. Trigger performances for single muons, pions and electrons with reconstructed $p_T > p_{Tcut}$ using the double stack geometry and an individual stack row correlation window cut of 3 pixels. Efficiencies are for reconstructed tracks with Monte Carlo p_T above p_{Tcut}. Average number of total and fake reconstructed tracks per event obtained under SLHC conditions.

p_{Tcut} (GeV/c)	ε_{Muon} (%)	ε_{Pion} (%)	$\varepsilon_{Electron}$ (%)	N_{Reco}	N_{Fake}
4	96.9	91.8	91.5	104.6	66.6
6	97.0	91.9	89.9	55.9	43.8
10	96.9	91.6	86.8	29.8	25.4

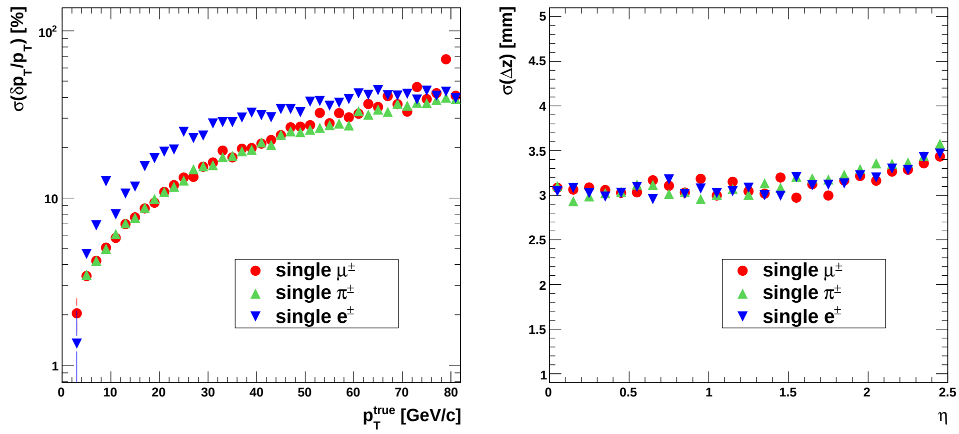

Figure 8. Left: Transverse momentum, and; Right: z vertex, (rms) resolutions for reconstructed $\mu^{\pm}$, $\pi^{\pm}$ and $e^{\pm}$ tracks using a double stack layer geometry. Results are for real tracks passing a 4 GeV/c p_T cut and a tight correlation window of 3 pixels for the individual stacks.

Figure 7 illustrates how tracks are reconstructed. Stubs from the inner stack are successfully correlated if they fall within a $\Delta\phi\Delta\eta$=0.02×0.1 window of the upper seed stub. The window size in $\Delta\phi$ must be large enough to accept low p_T tracks and to allow for multiple scattering within the inner layers. The $\Delta\eta$ window size is dominated by the size of the interaction region in z. The two stacked layers are placed at radii of 25 cm and 35 cm with coverage up to $|\eta| < 2.5$. Both layers use 100 μm thick sensors with a sensor separation of 2 mm. The transverse momentum is calculated using the two stubs and an assumed vertex at (0,0). This allows a variable cut on p_T (∼5-50 GeV/c) to be placed on the reconstructed track, as is performed in the current High Level Trigger [3]. Isolation performance for tracks with 2 GeV/c transverse momenta is not discussed here.

Table 2 shows that the number of reconstructed tracks is much lower than the number of stubs per layer while efficiencies are maintained for muons and pions. Due to electron bremsstrahlung, the electron efficiency falls as the p_T cut is raised. A large fraction of reconstructed tracks are combinatorial fakes; irreducible without reducing the $\Delta\phi\Delta\eta$ window or supplying additional matching information. However, since the total number of reconstructed tracks is small, this is not expected to be a problem once tracks are matched with calorimeter deposits or muon stubs. Studies measuring the simulated L1 triggering performance for objects such as muons and electrons under SLHC conditions are ongoing.

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Figure 8 shows that the transverse momentum resolution is measured to be $<20\%$ for muons and pions up to 50 GeV/c. Due to bremsstrahlung, the p_T resolution is slightly worse for electrons. The matching resolution at the calorimeter surface is measured to be $\Delta\phi\Delta\eta < 0.02\times0.15$. While the p_T resolution is certainly not acceptable for tracking, it does offer a coarse method for cutting on the transverse momentum so that trigger rates can be reduced if required. It also provides the trigger with an additional cut when matching tracks to calorimeter clusters by calculation of the E_T/p_T ratio or when matching to muon objects. Increasing the separation between the two stacks would improve the p_T resolution.

5 Summary

The CMS experiment plans to upgrade its tracking system in expectation of the LHC luminosity upgrade. The detector design will be driven by the requirements of the unique operating conditions at SLHC, a need to reduce material for improvement in detector and physics performance and the possibilities to provide tracking data to the L1 trigger. The stacked pixel layer concept has demonstrated viability for use at SLHC. Simulations show that a on-detector data reduction of $\sim$20 with $>$96% efficiency will be possible allowing transfer of data off-detector. Two stacked layers could be used for off-detector reconstruction of tracks with $\delta p_T/p_T < 20\%$ for p_T<20 GeV/c and with sufficient resolution so as to match tracks with L1 calorimeter objects. Further studies matching tracks to calorimeter deposits or muon tracks will determine whether combinatorial background will affect the L1 trigger rate or if a third stacked pixel layer is required to eliminate fakes. Significant challenges still remain in the realisation of such a system. The power consumption for a single layer is expected to be large and requires careful consideration as do cost and time for prototyping.

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